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National Bureau of Standards

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SUMMARY

Axial fatigue tests have been made by the resonance method on 10 specimens from airplane wing beams. The specimens contained several types of stress raiser, such as rivets, holes, fittings, splices, reinforcing plates, and so forth. Some of the beams had been in flight service; some had not. The method of obtaining resonant axial vibration and results for the first two wing beams already have been reported in NACA TN No. 660. Axial fatigue tests were made, in addition, on coupon specimens machined from the flanges. The tests were made in a direct tension-compression fatigue machine using lubricated solid guides to prevent buckling. Some of the specimens were nominally free from stress concentrations; others had a 0.1285-inch drilled hole at midlength where the width was 3/8 inch. In addition, coupon specimens consisting of parallel strips of sheet metal joined by idle rivets were tested.

The wing-beam specimens which had not been in service were found to be stronger in fatigue than those which had. All wing-beam specimens showed a much higher stress concentration factor in fatigue than did the coupons containing holes or idle rivets. It is believed that a web splice near which failure occurred in most of the wing-beam specimens accounts for this discrepancy by causing a damaging stress concentration.

INTRODUCTION

In 1935 the National Bureau of Standards started an investigation at the request of the NACA to determine the axial fatigue strength of airplane wing beams. The beams were loaded by the resonance method in a manner similar to that developed by the Goodyear Zeppelin Corporation (reference 1). Results for the first two wing beams together with details of the test method were reported in reference 2. Eight more wing-beam specimens have since been tested, thereby completing the program.

The purpose of the investigation was to determine the effect on the fatigue strength of a full-size structure of several important types of stress concentration and to determine whether it was practicable to design such a structure on the basis of test results obtained on small, relatively simple coupon specimens containing typical stress raisers.

It was decided to test the wing-beam specimens under alternating axial load rather than under alternating flexural load. Although flexural loading corresponds more closely to service conditions, it would be difficult to analyze the results of flexural tests because of the various fittings, holes, reinforcing plates, and other changes in cross section which were present. It was believed that axial loading would have practically the same effect on the flanges as flexural loading; in addition, axial fatigue tests by the resonance method presented a means of applying a large number of nearly sinusoidal load cycles in a short time.

The technique used in the fatigue tests of the wing-beam specimens is due principally to William M. Bleakney, who conducted the project from 1935 to 1939. He adapted the method developed by the Goodyear-Zeppelin Corporation for testing airship girders to wing-beam specimens making use of motor-generator sets, available at the National Bureau of Standards. The technique, together with the results for the first two specimens, is given in reference 2. Dr. Bleakney left the Bureau in 1939 and the project was taken over by Mr. F. C. Roop, who conducted it until 1941. He placed in operation, beginning with specimen 4, an automatic control circuit designed by Dr. Bleakney for holding the exciting frequency more nearly at resonance, and tested specimens 3 to 8. The remaining two specimens were tested by Philip Krupen, who also computed the results for the wing-beam specimens. Axial fatigue tests of coupon specimens machined from the wing-beam flanges were made by W. C. Brueggeman with the assistance of M. Mayer, Jr., and W. H. Smith.

This investigation, conducted at the National Bureau of Standards, was sponsored by and conducted with the financial assistance of the National Advisory Committee for Aeronautics.

WING-BEAM SPECIMENS

The specimens were taken from the wing beams of biplanes which had been particularly susceptible to vibration in flight. Three complete upper wings were furnished by the Bureau of Aeronautics. One was from an airplane which had not had any flight service; the other two had been subjected to more than 200 hours of flight. Ten specimens, shown in figures 1 and 2, were cut from the beams of these wings. The number of hours of flight service and the location of the specimen in the wing are given in table 1.

The specimens consisted of T-section 24S-T aluminum-alloy extrusions riveted to each edge of an aluminum-alloy web as shown in figure 3. The skin and ribs had been cut off near the flanges when the specimens were removed; however, the rivets which joined these members to the flanges were not disturbed except when unavoidable. Each specimen had numerous ribs, fittings, and reinforcing plates fastened by rivets, self-tapping screws, and bolts. Cut-outs and large holes in the web were generally reinforced; however, the maximum reduction in cross section due to unreinforced holes was as much as one-sixth in specimen A. The web of each specimen except A was spliced near the small end.

All specimens except A were tapered slightly; in addition, those taken from the front beams were reinforced by a doubler plate extending over about one-fourth the length. The web of the specimens taken from the front beams was tapered by an amount which caused as much as 3 percent variation in the cross-sectional area of the specimen from one end to the other. The rear beams except A were tapered both by gradual variation in the depth of the web and by stepwise variation in the thickness of one flange. The flange thickness was constant at its minimum value for a length of about a foot at the small end. The taper of the web in this length caused a variation of 1 or 2 percent in the cross-sectional area of the specimen. The minimum cross-sectional area ranged from 0.93 to 1.16 square inches. The length was about 6 feet.

TESTS

The equipment and the general method of testing are described in reference 2. The procedure consisted essentially of clamping large masses to each end of a specimen and causing these to vibrate axially with respect to each other at a natural frequency determined by their mass and the axial spring constant of the specimen. Electric reciprocating motors consisting of a cylindrical field coil and a ring armature guided by flexure plates were used to excite the vibration. The vibrating mass at each end included a field magnet weighing 580 pounds and clamping fixtures weighing 110 pounds, total 690 pounds.

Figure 4 shows an electric circuit diagram for the reciprocating motors. The field coils F of the reciprocating motors are connected in series and carry direct current which is controlled by the variable resistances R_4 and R_5. The armatures are supplied by an alternating-current generator the frequency of which is maintained at resonance by controlling the speed of the direct-current motor which drives it as follows:

The field resistance R_6 of the direct-current motor is set so that the frequency of the alternating-current generator is slightly above resonance. An increase above resonance in the frequency of the alternating-current supply to the armature is accompanied by an increase in the current through the winding of the relay R because the armature current required by the direct-current motor also increases with the speed. The relay R is sensitive to this armature current and closes when the current increases to a critical value. When R closes, the grid bias on the 885 mercury vapor tube becomes less negative.

This vacuum tube also responds to an increase in the speed in another way. The reciprocating motor armatures together with R_3, L, and R_2 form a bridge circuit; the alternating-current input to the transformer T increases with the frequency because the inductance in two of the legs of the bridge causes a phase difference which increases with the frequency. Thus an alternating-current electromotive force is superimposed on the direct-current grid bias.

These two effects increase the potential of the grid when the speed is above resonance and cause current to flow from the filament through the direct-current motor field, decreasing the motor speed and the alternating-current frequency. The relay R then opens and the cycle repeats. In operation, R opened and closed about five times per second. The particular values of the resistances in figure 4 are not given because they were frequently changed; however, the values ranged between 10 and 60 ohms.

Details of the reciprocating-motor terminal attachments are given in reference 2. The attachments for specimens 3 to 10 were similar to those described for specimen B.

The specimen was alined with respect to the reciprocating motors by means of four Tuckerman optical strain gages mounted on the flanges, two near each end. The autocollimator used with these gages was equipped with a dumbbell reticule. The gages were read while the reciprocating motors were operated at a low load. The terminal fixtures were unclamped and shifted until the strain indicated by each of the four gages was within 5 percent of the average. At the same time, the distance between the reciprocating motors was set so that the maximum tensile and compressive loads on the specimen were equal. Adjustments were made to minimize bending and twisting as measured by the amplitude of the front-face image of the reticule reflected from the Tuckerman strain gage.

With the adjustments described, it is believed that the load was essentially axial and completely reversed. The specimen was subjected to 200,000 to 2,000,000 cycles of loading during the adjustment, but these were not counted because the average stress never exceeded 3500 psi.

After the specimen had been alined, it was necessary only to increase the amplitude of vibration to conduct a test. The strain gages were left in place and readings were taken periodically. These were used later to compute the stress.

The average resonant frequency for the different specimens was between 54.0 and 79.1 cycles per second. The number of cycles N was determined for the first three specimens by periodic readings of the frequency and the elapsed time of a test. Starting with specimen 4, an electric clock was connected in parallel with the reciprocating motor armatures. The clock was equipped with such a dial that N could be read directly.

A photographic record of strain as a function of time was obtained for a Tuckerman gage mounted on the flange of a specimen by means of a recorder built by the NACA. A portion of a record (fig. 5) shows the strain variation with time to be nearly sinusoidal.

The test of each specimen was continued until one flange had fractured. Failure was accompanied by a sharp cracking sound. It was observed that the resonant frequency suddenly would drop about 5 cycles per second, a few minutes before failure. Simultaneously, the load dropped too fast to maintain resonance. After failure no natural vibration could be induced.

Specimen 4 was run at a stress of 4200 psi for 52,000,000 cycles (designated 4a); the stress was then increased to 5700 psi, and failure occurred after 7,500,000 cycles (specimen 4b).

Considerable lateral vibration was encountered when testing specimen 8. After about 500,000 cycles the unsupported portions of the web began to vibrate loudly; shortly thereafter the whole system began to vibrate perpendicularly to the plane of the web. The double amplitude at the middle of the beam was about 2 inches. Attempts to snub out this undesired mode of vibration proved ineffective. It is probable that N for this specimen was lowered by this lateral vibration.

Although the electrical control performed well in maintaining constant frequency, some trouble was caused by a change in the resonant frequency due to heating of the reciprocating motors. This caused the load to fall off until the change was detected and the frequency readjusted to resonance. To take into account these occasional periods of nonresonant operation, the strain was observed periodically.

The stress which was computed from the strain, and the corresponding observed number of cycles were weighted by the following somewhat arbitrary formula to obtain values for the S-N curve. The weighting takes into account occasional periods when the strain was less than 95 percent of the nominal value for the test, a condition which prevailed about 10 percent of the time.

$$S = E\epsilon_n \frac{N_n}{N} + \frac{E}{4N} \sum N_1 \epsilon_1$$

$$N = N_n + \frac{N_1}{4}$$

where

S stress for a point on the S-N curve

N number of cycles for a point on the S-N curve

ϵ_n normal strain (not less than 95 percent of nominal value)

N_n cycles of normal strain

ϵ_l low strain (less than 95 percent of nominal strain)

N_l cycles of low strain

E Young's modulus, 10,570 ksi

Half the double amplitude of ϵ_n and ϵ_l was used in the formula.

Fatigue Tests of Coupons from Wing Beams

In order to compare the fatigue strength of the structure with that of its material, coupon specimens (fig. 6, type I) were machined from the flanges of some of the wing beams and tested in a direct tension-compression axial fatigue testing machine by means of a technique described in reference 3.

The specimens were taken at locations such that the reduced section would be remote from stress raisers in the wing beam. The stress to which this material had been subjected during the test of the wing beam was therefore insufficient to affect the fatigue strength appreciably. The specimens were machined by means of a process described in reference 4. The thickness of the specimen was the full thickness of the flange, about 0.142 inch. It was necessary to machine off the stem of the T and the accompanying fillets flush with the inner surface of the flange; this resulted in a machined surface extending over about half one face.

In addition to the type-I specimens which were nominally free from stress raisers, types II and III (fig. 6) were tested to determine whether results for coupons containing several typical stress raisers could be correlated with those obtained on the full-size structure. Type II also was machined from the flanges. It contains a 0.1285-inch hole, the size generally used for 1/8-inch rivets, at mid-length;

otherwise it is the same as type I. Type III consists of two parallel strips of 0.032-inch 24S-T sheet joined by idle rivets. Idle rivets were used since, under the test conditions for the wing-beam specimens, most of the rivets were of this character. The lateral guides which were used to prevent buckling of type-III specimens were similar to those shown in reference 3, except that the bars contained holes to provide clearance for the rivet heads.

The specimens were tested in the direct tension-compression fatigue machine shown in figure 7. This machine is an adaptation of one designed by the Aluminum Company of America. It is described in reference 4.

The stress in the coupons was computed by dividing the load by the product of the thickness and the net width at a rivet hole.

Static Tests of Material

Static tensile and compressive properties of specimens machined from the flanges of some of the wing beams are given in table 2. Typical stress-strain curves are given in figure 8. S-N data for all specimens are given in figure 9; the fatigue stress concentration factor k_f which is defined as the ratio of the fatigue strength of coupon specimens of the material nominally free from stress raisers to the fatigue strength of the wing-beam specimens or drilled coupons is given in figure 10. The idle-rivet coupons showed so much scatter that k_f was not plotted. However, the results lie between those for the plain coupons and those for the drilled coupons. A description of the failure of each wing-beam specimen follows.

<u>Specimen A, figure 11:</u> Fracture passed through a 13/16-inch unfilled hole on the center line of web, and three filled rivet holes in the flange. Six other web cracks were found in the flange and are shown in reference 2, figures 22 and 23.

<u>Specimen B, figure 12:</u> The web and flange cracked at adjacent rivets; in addition, the web cracked at the terminal fixture. Both cracks were remote from the web splice. All flange cracks occurred in the same flange and all web cracks started at rivets passing through this flange.

Specimen 3, figure 13: Failed at web splice. Cracks extended through rivet holes in web, butt strap, and flange. In addition, a crack originated at about 6,700,000 cycles in the web at the end of a doubler-plate reinforcement and at the time of the principal failure had penetrated into the stem of both flanges through rivet holes.

Specimen 4, figure 13: Failed at web splice. The fracture extended through the outer row of rivets at the splice and the stem rivet of the flange. A crack was first noticed at the stem rivet at about 6,800,000 cycles (specimen 4b).

Specimen 5, figure 14: Failed through web splice and stem rivet of flange. Crack is believed to have started in web at about 2,000,000 cycles.

Specimen 6, figure 14: Flange failed opposite web splice. A crack was first noticed at about 10,000,000 cycles at a rivet hole in the outside of the flange and spread inward toward the stem.

Specimen 7, figure 15: Failed opposite web splice in the same manner as specimen 6 except that the fracture passed through unfilled rivet holes. A crack was first noticed about 100,000 cycles before fracture.

Specimen 8, figure 15: Failed near web splice in the same manner as 6 and 7. Crack first noticed about 140,000 cycles before fracture.

Specimen 9, figure 16: Failed at web splice in the same manner as specimen 5.

Specimen 10, figure 17: Web failed at splice and flange cracked through a stem rivet.

All type-II specimens failed at the hole. All type-III specimens failed at the rivet holes.

DISCUSSION

A smooth curve may be drawn through the plotted points in figure 9 with the exception of point 8; there is less scatter than usually is expected in fatigue results. The lateral vibration of specimen 8, as previously mentioned, may account for the low position of point 8.

The unused wing beams had a higher fatigue strength than the used. This indicates that a certain amount of fatigue damage had already occurred in service. Coupons machined from both kinds of beam did not show this effect, probably because the coupons did not include stress raisers at which damage would originate.

The results for both the plain and the drilled coupons are about the same as those previously obtained on 0.032-inch 24S-T sheet, which are reported in reference 4; k_f for these specimens is plotted in figure 10 for comparison.

The results for the idle-rivet coupons show considerable scatter and are intermediate between those for the plain and those for the drilled coupons.

Figure 10 shows that the fatigue stress concentration factor k_f for the wing beams is much higher than that for either the drilled or the riveted coupons; this indicates the presence of other, more damaging stress concentrations than that due to small rivet holes and idle rivets.

It will be noted that 8 of the 10 wing-beam specimens failed near one end, and that of the 9 specimens containing a web splice 8 failed at the splice and the flange of the ninth was practically at the point of failure at the time that the principal failure occurred elsewhere. Although the minimum cross-sectional area occurred at one end, the taper is judged to be so slight, at least over an appreciable length at the small end, as to be insignificant. The splice, however, may produce an important local stress concentration. The splice is undoubtedly less rigid than the solid flanges which are in parallel with it; hence the load which is carried by the web at a location remote from the splice must be transferred to the flanges by the rivets joining the flanges to the web near the splice. Thus these rivets become active rivets. It is difficult to estimate the distribution of load among the rivets and the stress concentration factor at such rivets. In general, the few available results of fatigue tests on riveted joints where the rivets are active indicate a much higher value of k_f than for idle rivets or empty holes. Thus the splice may cause a notch effect by the transfer of load from the web to the flanges and by the fact that a high stress concentration may occur at the rivets which transfer this load.

Specimen A, which was unspliced, failed at a 13/16-inch unfilled hole in the web; k_f was only slightly higher than the theoretical value of about 3, although still appreciably higher than the factor obtained on type-II specimens. It is believed that there is a possibility of size effect here. Such an effect has been observed in another investigation of the fatigue strength of strips containing holes, but these tests are as yet too incomplete to estimate this effect for specimen A.

The curve in figure 9 for the wing-beam specimens was drawn through the point A, although the fact that the web was not spliced placed this specimen in a different category from the others. It may be that point A should lie above a curve representing the fatigue strength of spliced specimens.

When evaluating the injurious effect of stress raisers it must be remembered that the beams were designed for transverse loads and tested under axial loads. The notch effect of the web splice is probably more severe under axial load than under transverse. Stress raisers located on the neutral axis, as, for instance, the hole shown in figure 11, would not be objectionable under transverse loading. Furthermore, the value of the bending moment would vary along the length of the beam and might be low enough to be safe at a stress raiser which would cause failure under axial fatigue loads.

CONCLUSION

Axial fatigue testing of wing beams by the resonance method is a tedious, somewhat difficult process requiring considerable time and equipment.

Wing beams which had been in service had a lower fatigue strength than new beams. The results show a greater fatigue stress concentration factor for the wing-beam specimens than for drilled coupons machined from the flanges or for parallel strip coupons containing idle rivets. Thus the investigation fails to disclose a method for determining the fatigue strength of a large, complicated structure by fatigue tests of small, relatively simple specimens.

The relatively high stress concentration factor is believed to be caused principally by the notch effect of web splices in most of the specimens. Time did not permit a study of the stress concentration due to web splices.

National Bureau of Standards,
Washington, D. C., July 10, 1944.

REFERENCES

1. Goodyear-Zeppelin Corporation: Preliminary Fatigue Studies on Aluminum Alloy Aircraft Girders. NACA TN No. 637, 1938.

2. Bleakney, William M.: Fatigue Testing of Wing Beams by the Resonance Method. NACA TN No. 660, 1938.

3. Brueggeman, W. C., and Mayer, M., Jr.: Guides for Preventing Buckling in Axial Fatigue Tests of Thin Sheet-Metal Specimens. NACA TN No. 931, 1944.

4. Brueggeman, W. C., Mayer, M., Jr., and Smith, W. H.: Axial Fatigue Tests at Zero Mean Stress of 24S-T Aluminum-Alloy Sheet with and without a Circular Hole. NACA TN No. 955, 1944.

TABLE 1

FLIGHT SERVICE AND LOCATION OF WING-BEAM SPECIMENS

Specimen	Flight service (hr)	Location			
		Front	Rear	Starboard	Port
A	238		x	middle	
B	238	x		middle	
3	212	x			x
4	0		x		x
5	0		x	x	
6	212	x		x	
7	0	x			x
8	0	x		x	
9	212		x	x	
10	212		x		x

TABLE 2

PROPERTIES OF MATERIAL OF WING-BEAM FLANGES

Beam	Tensile or compressive; upper or lower	Yield strength (ksi)	Ultimate (ksi)	Young's modulus (ksi)	Elongation in 2 in. (percent)
3	T U	49.0	65.2	10,300	21
	C U	42.7		10,610	
	T L	49.7	66.2	10,280	20
	C L	42.3		10,840	
4	T L	47.9	64.3	10,590	20.5
	C L	40.9		10,820	
5	T L	47.1	63.1	10,350	24
	C L	40.8		10,850	
6	C L	43.3		10,570	
10	T L	53.0	72.1	10,240	18
	C L	44.7		10,770	
Av.	T			10,350	
Av.	C			10,740	
Av.	T and C			10,570	

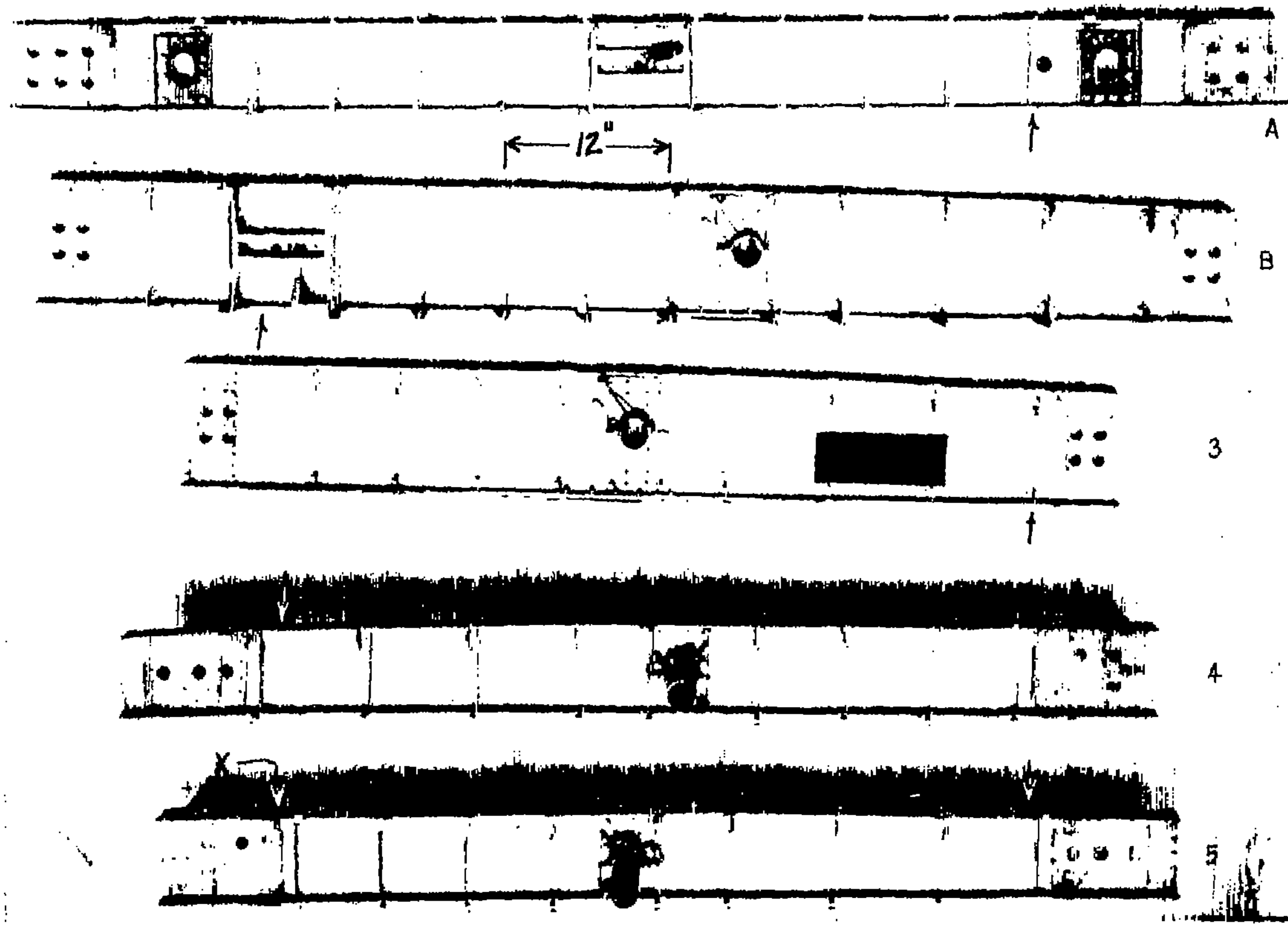


Figure 1.- Specimens A, B, 3, 4, and 5 after failure. The extent to which the specimens were imbedded in the terminal fixture is shown by the discolored area at the ends. Arrows indicate the principal failure.

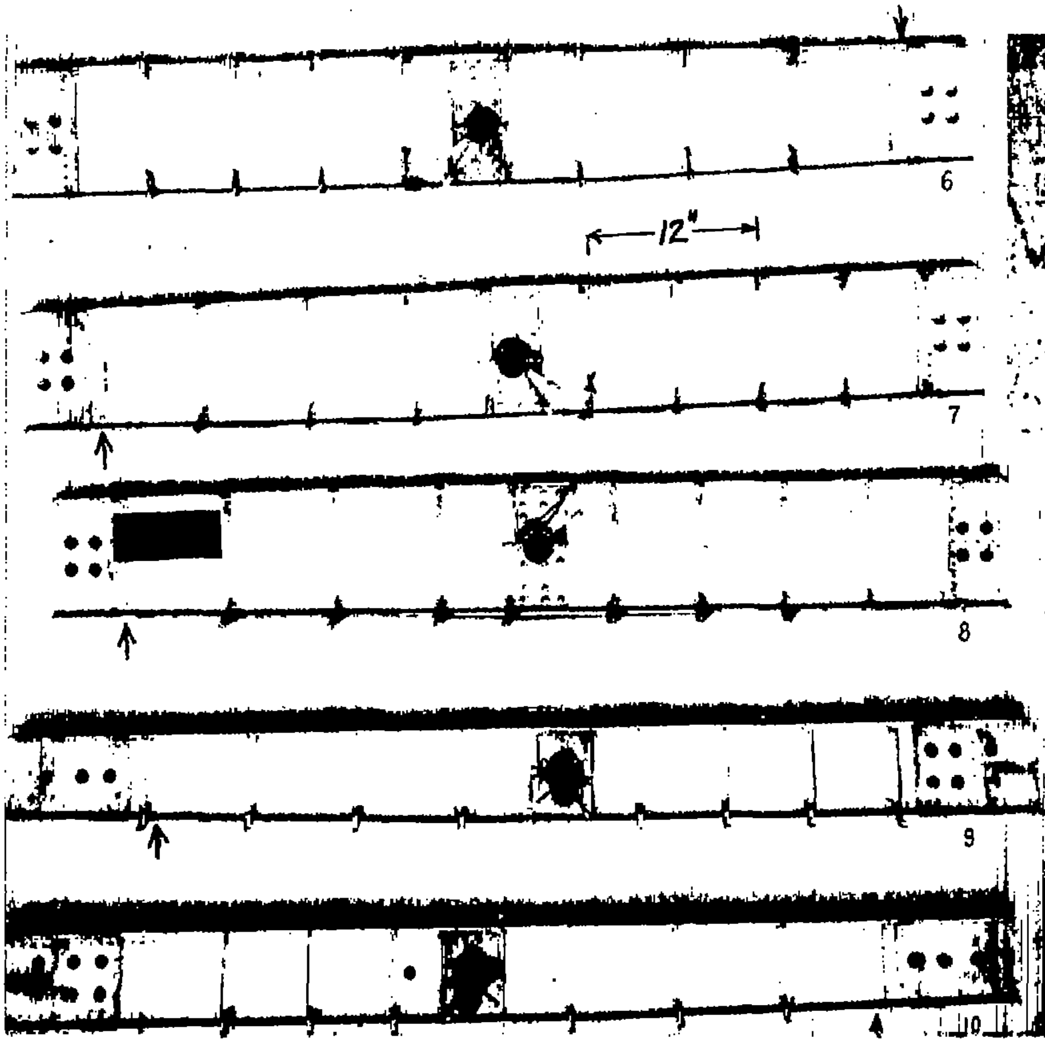


Figure 2.- Specimens 6 to 10 after failure.

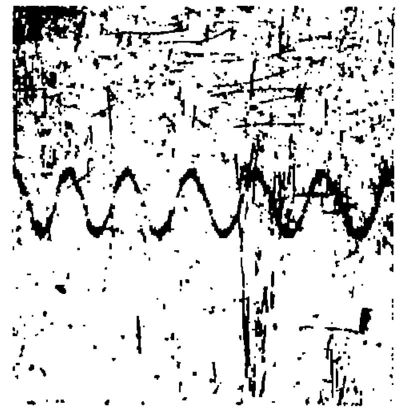


Figure 5.- Wave form of the strain vibration. The frequency is about 65 cps.

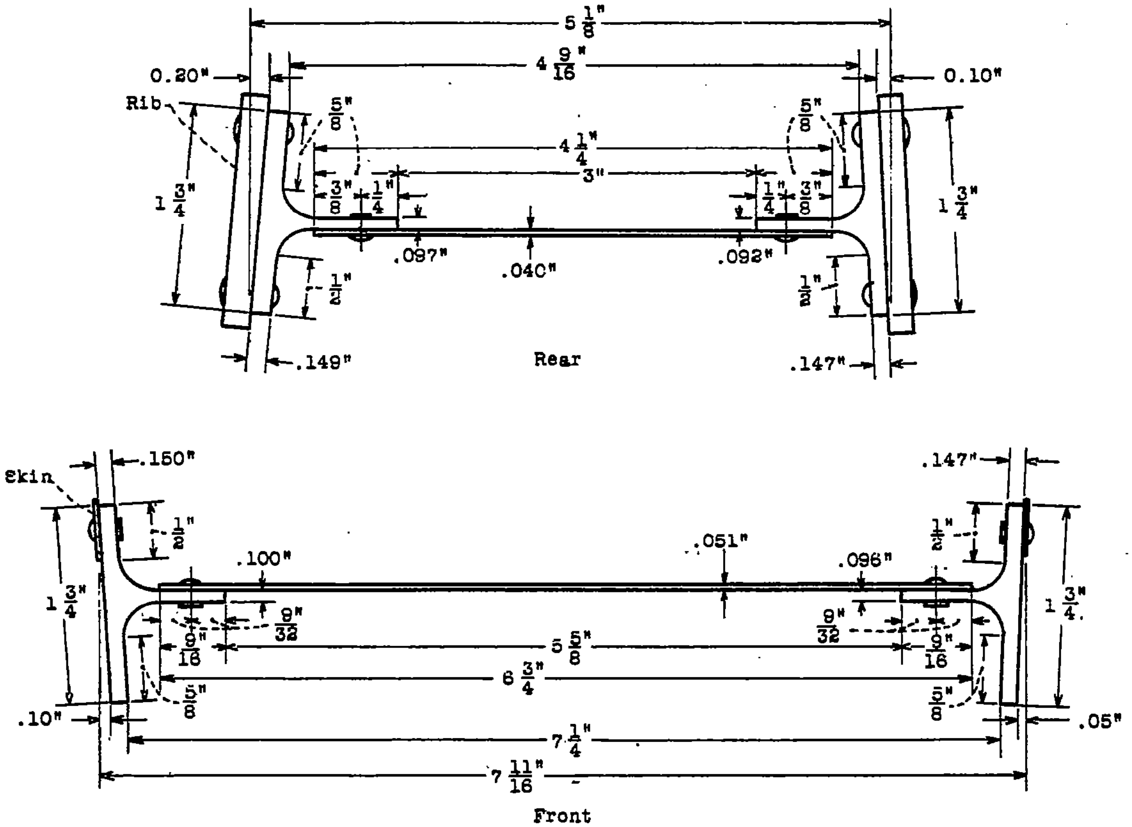


Figure 3.- Cross section of wing-beam specimens.

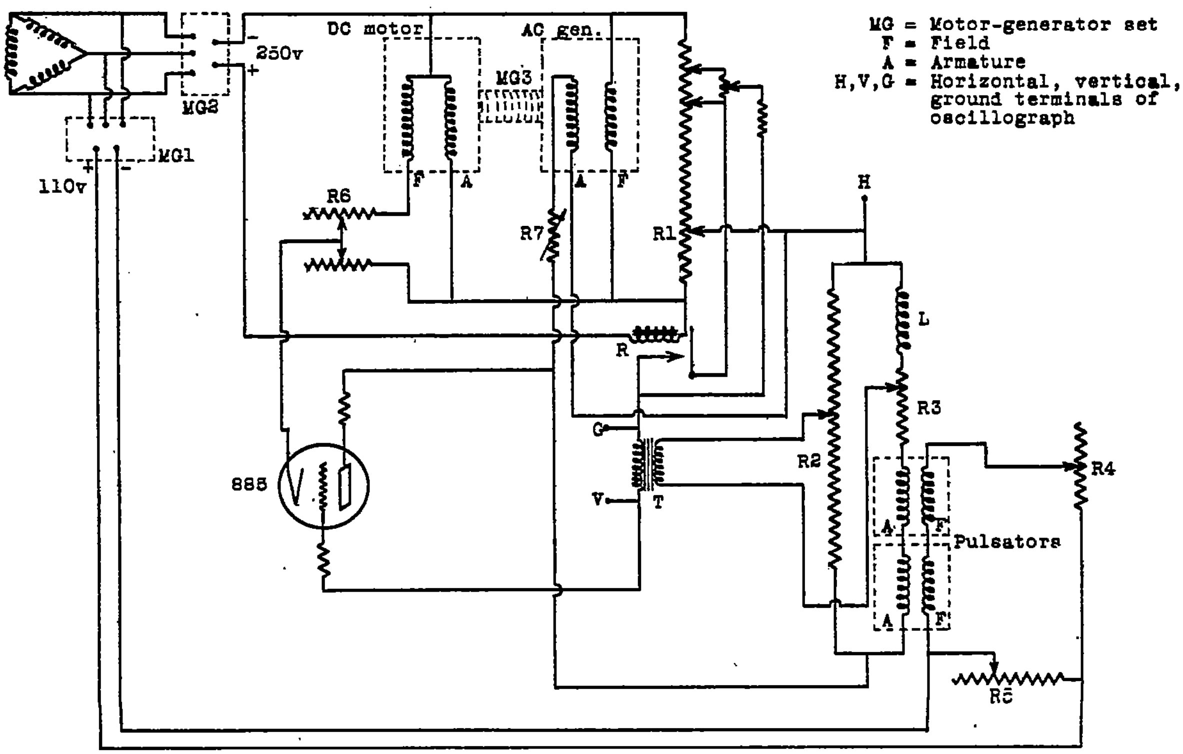


Figure 4.- Electric circuit for reciprocating motors.

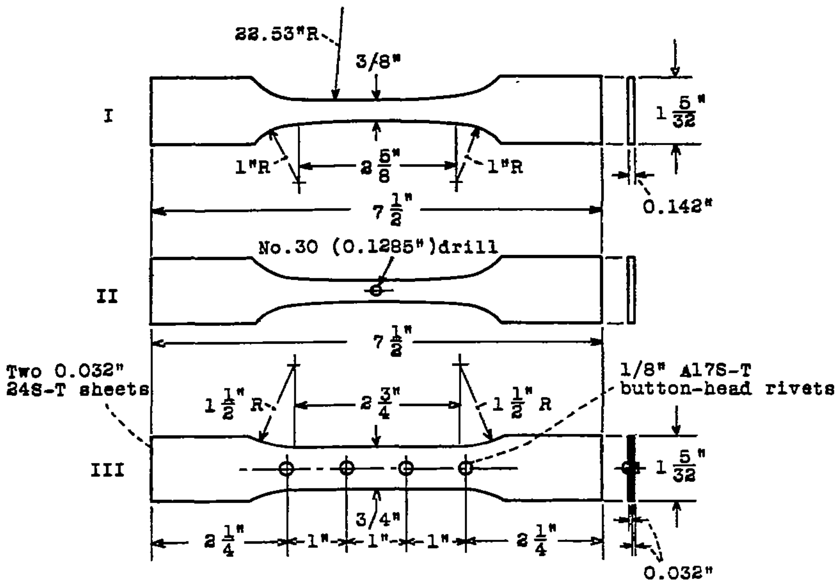


Figure 6.- Coupon specimens I and II machined from the wing-beam flanges and idle-rivet specimen III.

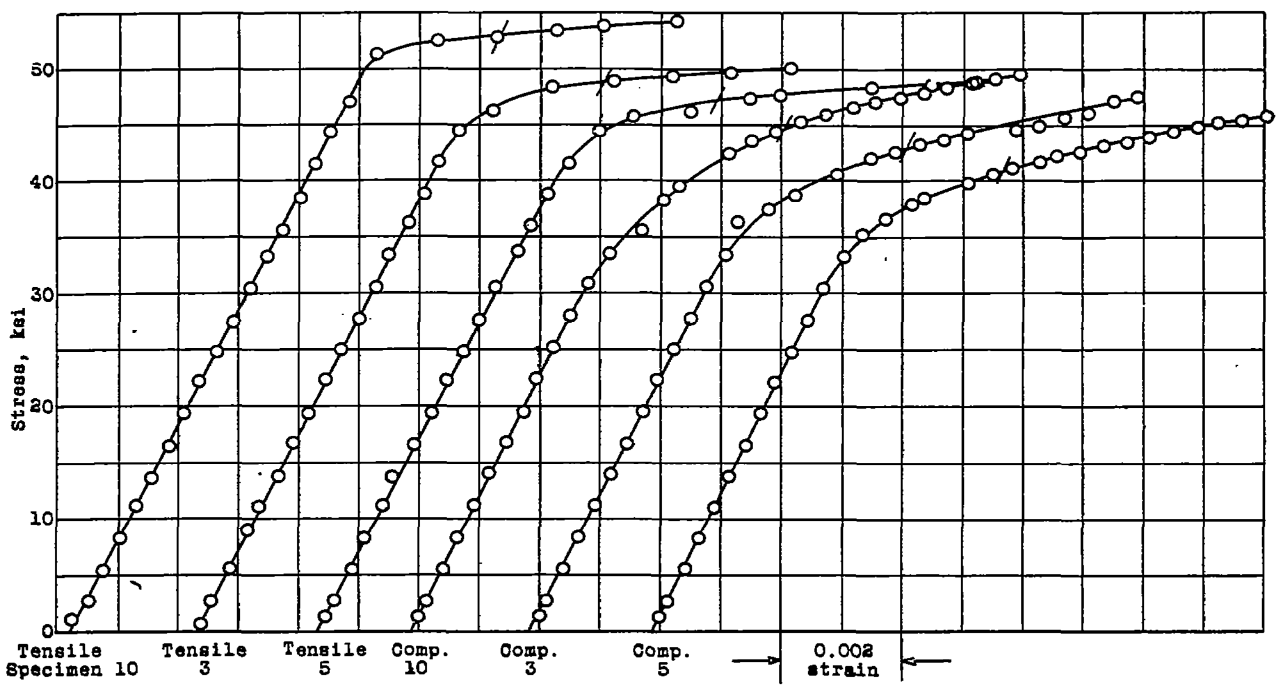


Figure 8.- Typical static tensile and compressive stress-strain curves obtained on specimens machined from the wing-beam flanges.

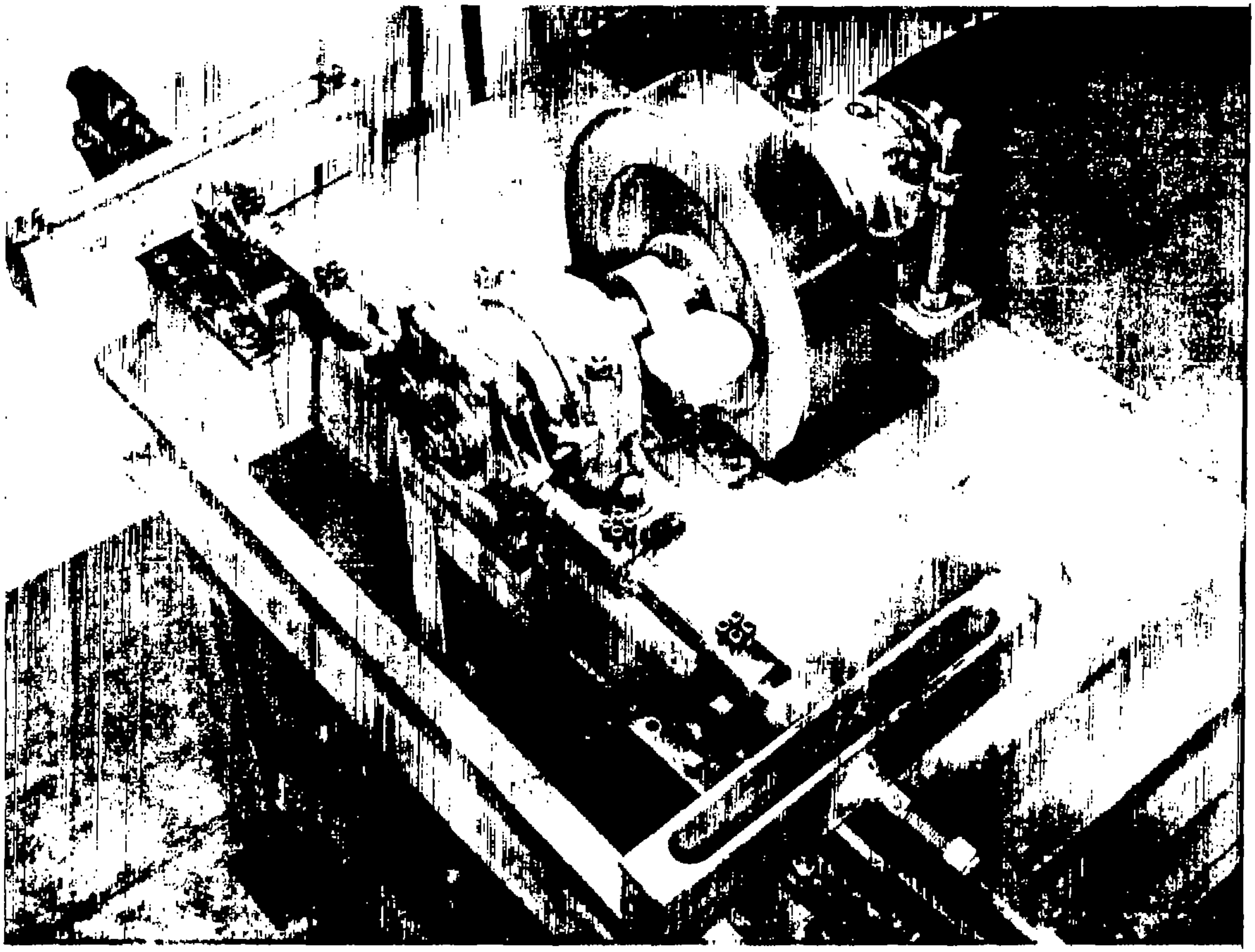


Figure 7.- Axial tension-compression fatigue machine.

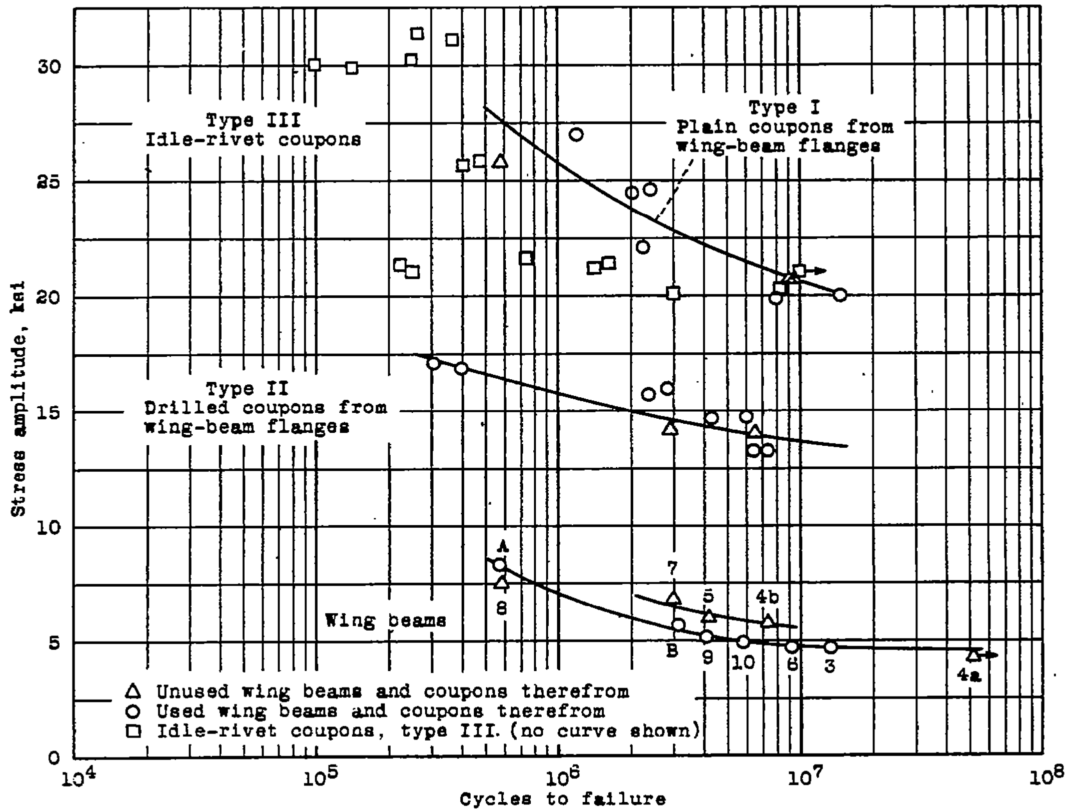


Figure 9.- S-N curves for wing beams and coupons.

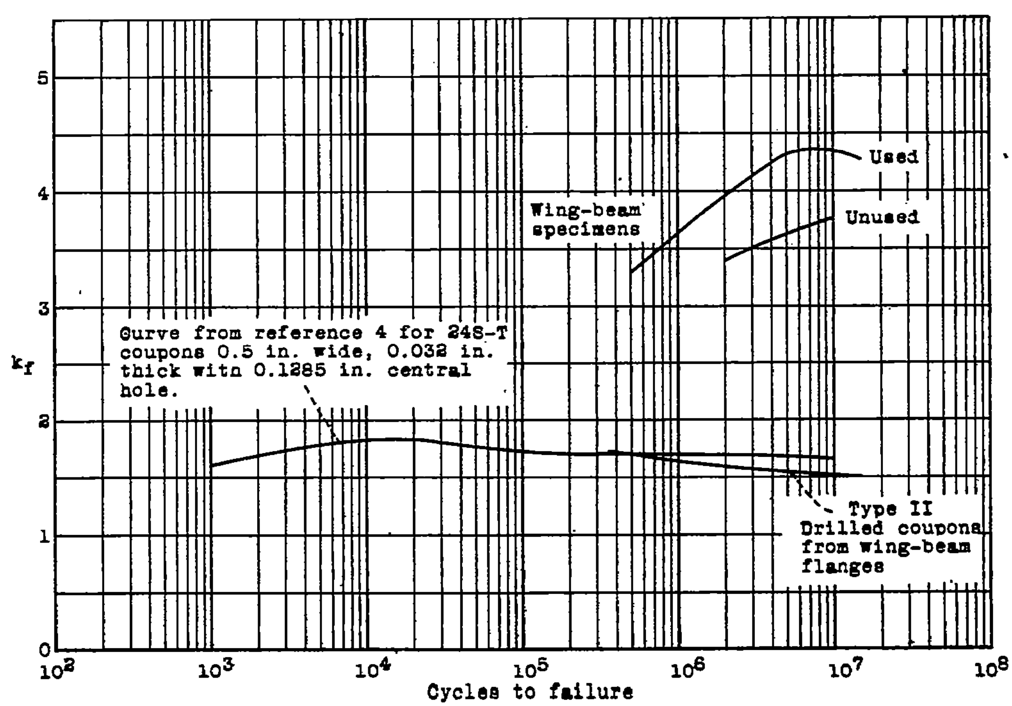


Figure 10.- Fatigue stress-concentration factors for wing-beam specimens and coupons.

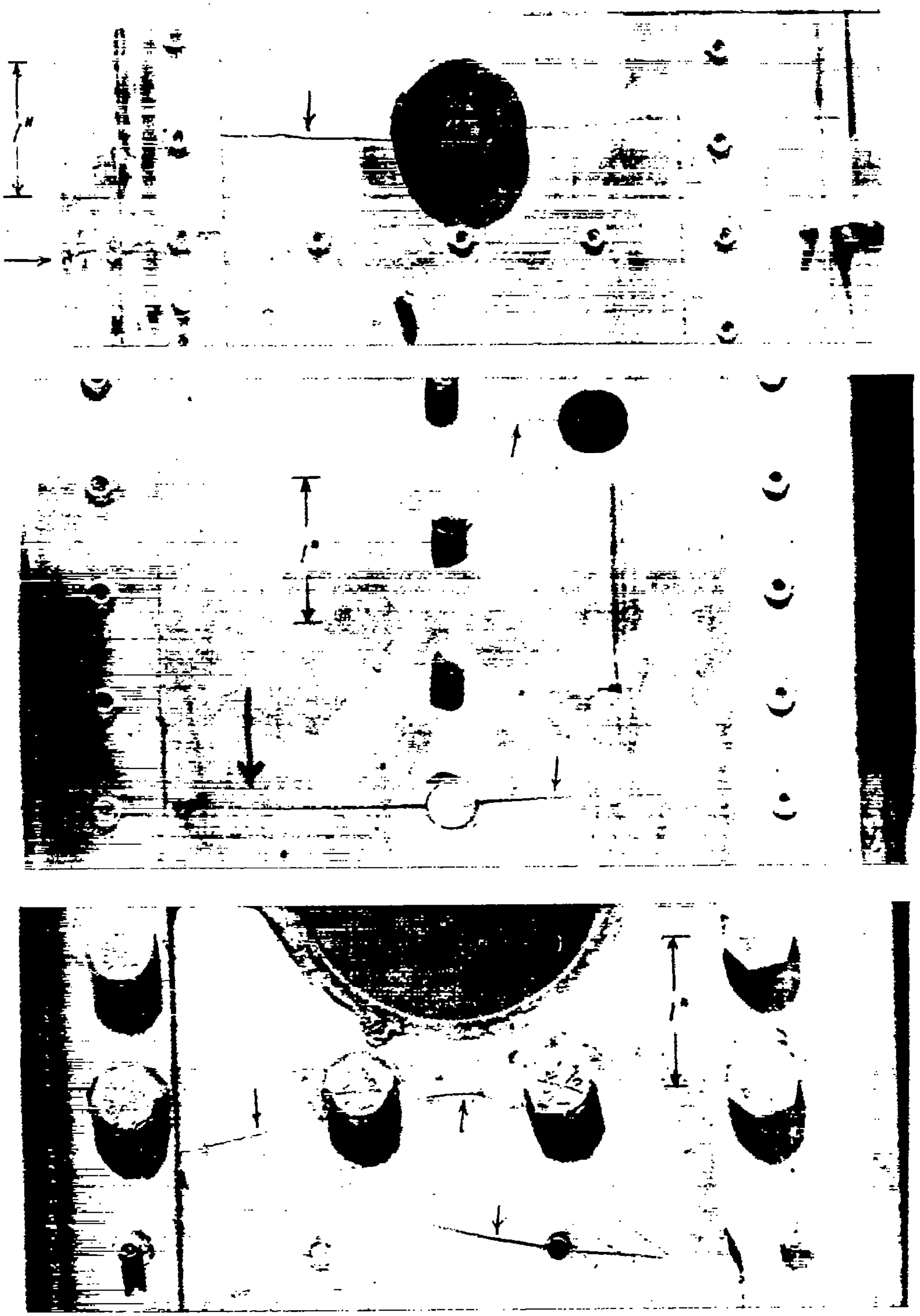


Figure 11.- Fatigue cracks and fracture of specimen A. The principal failure which passes through three rivet holes in the flange and a $\frac{13}{16}$ -inch grommeted hole in the web is shown at the top. The two holes in the flange were occupied by rivets fastening a portion of a rib; this was removed after failure to expose the fracture.

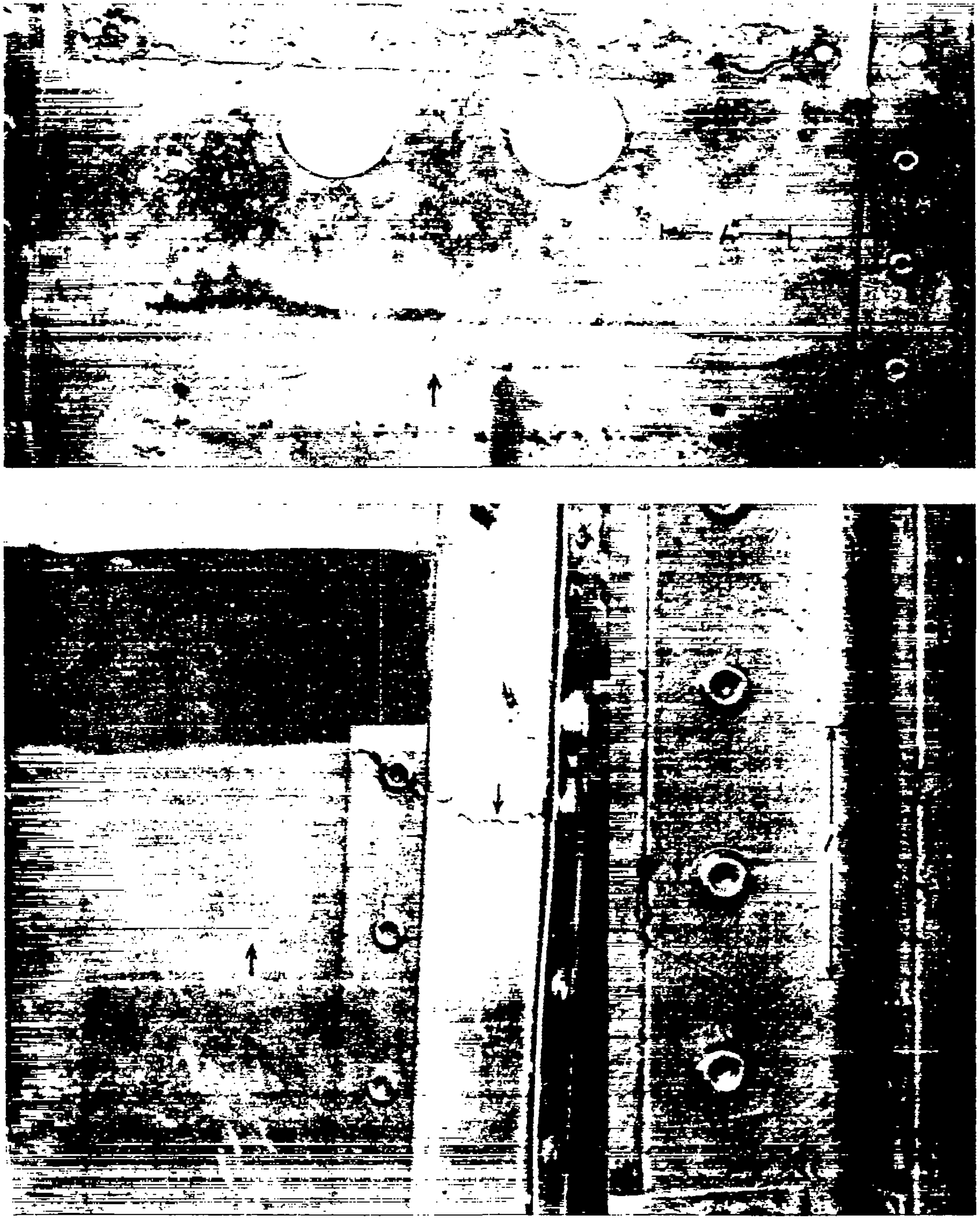


Figure 12.- Failure of specimen B. The principal failure is shown at the lower left. The crack at the lower right is located at the web splice. A web crack at the terminal fixture is shown at the top

Figure 13.- Fractures of specimens 3 and 4.

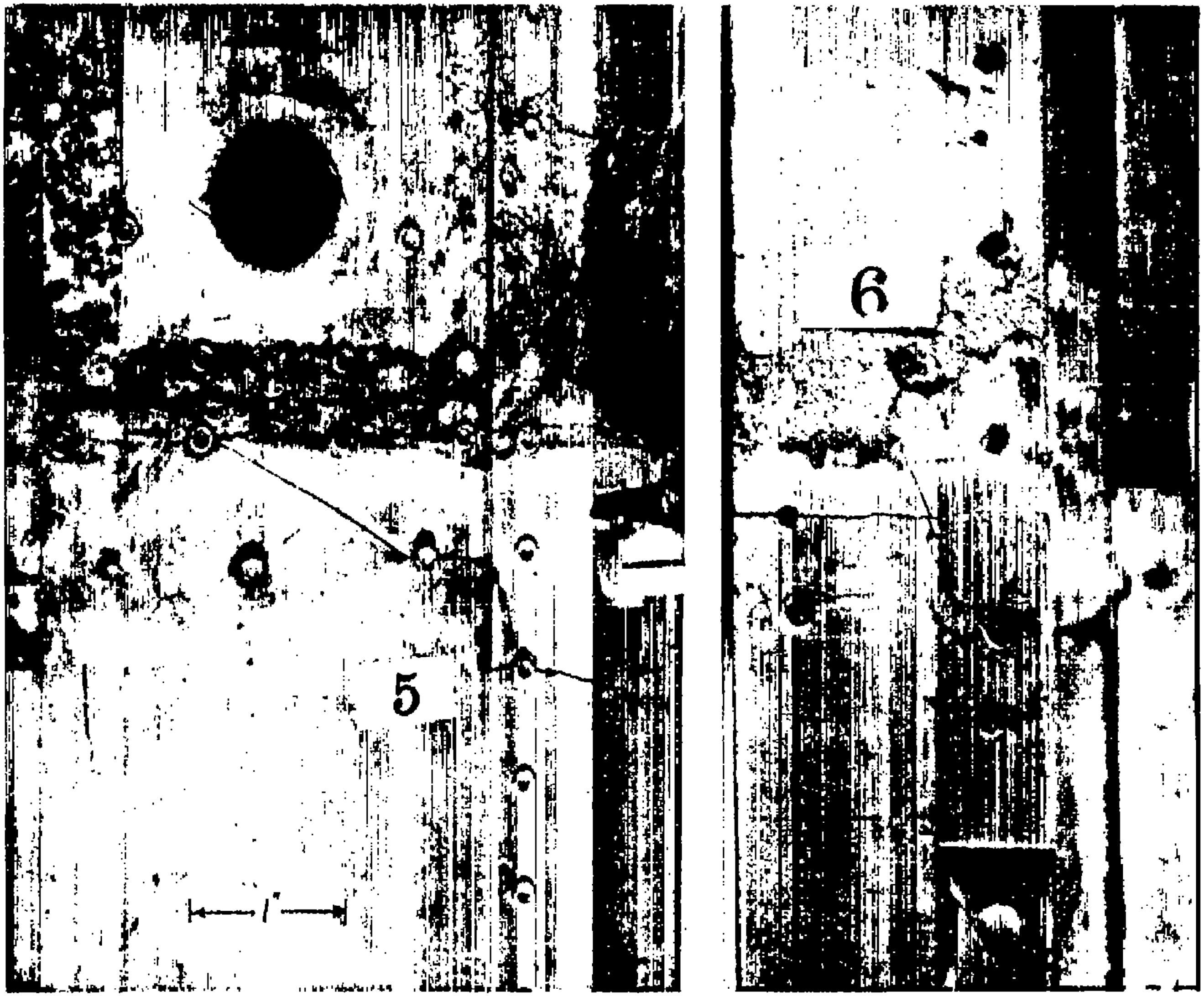


Figure 14.- Fractures of specimens 5 and 6.

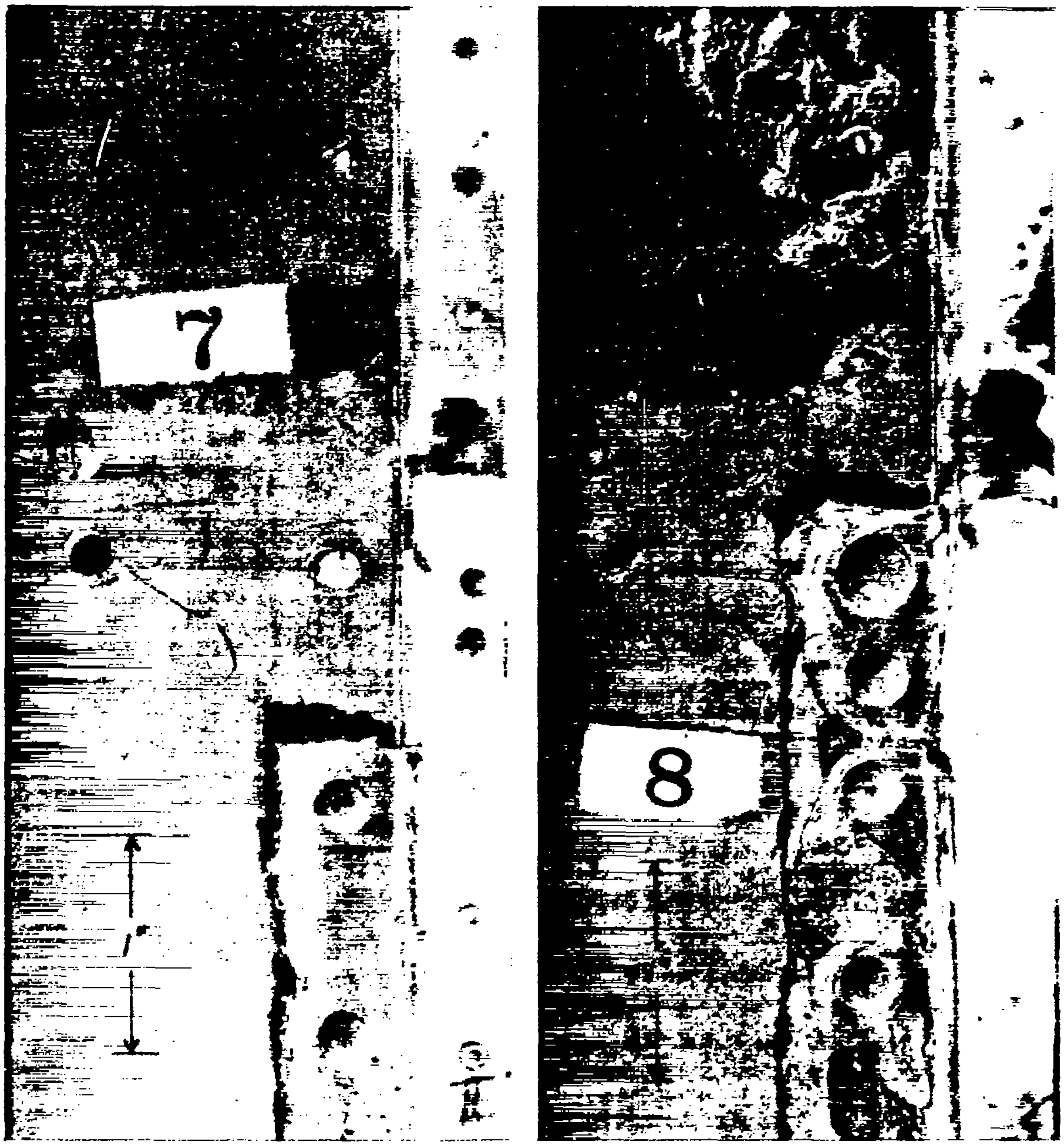
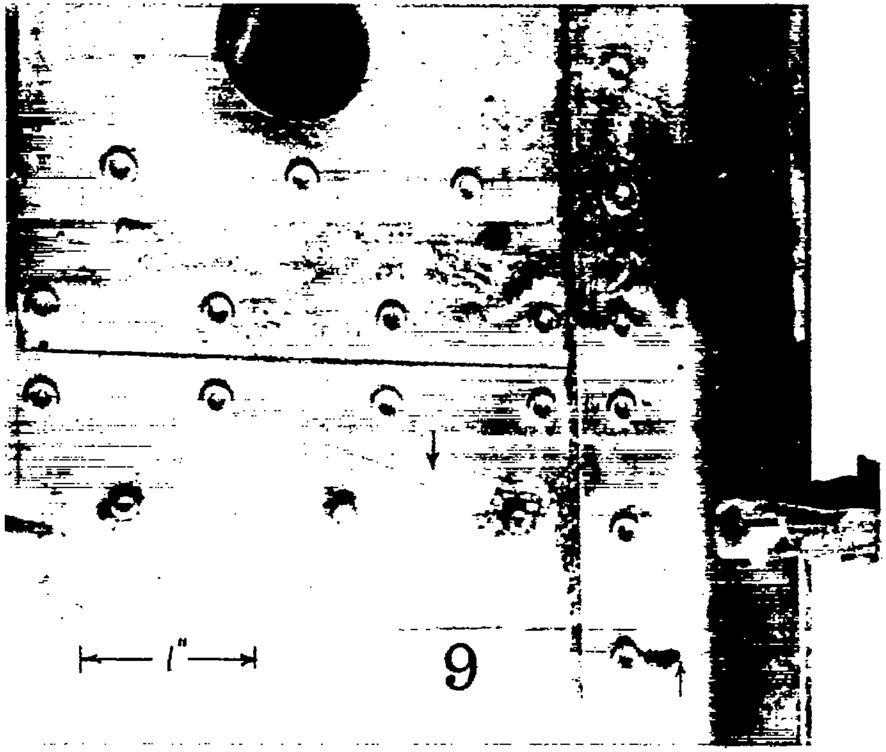


Figure 15.- Fractures of specimens 7 and 8.



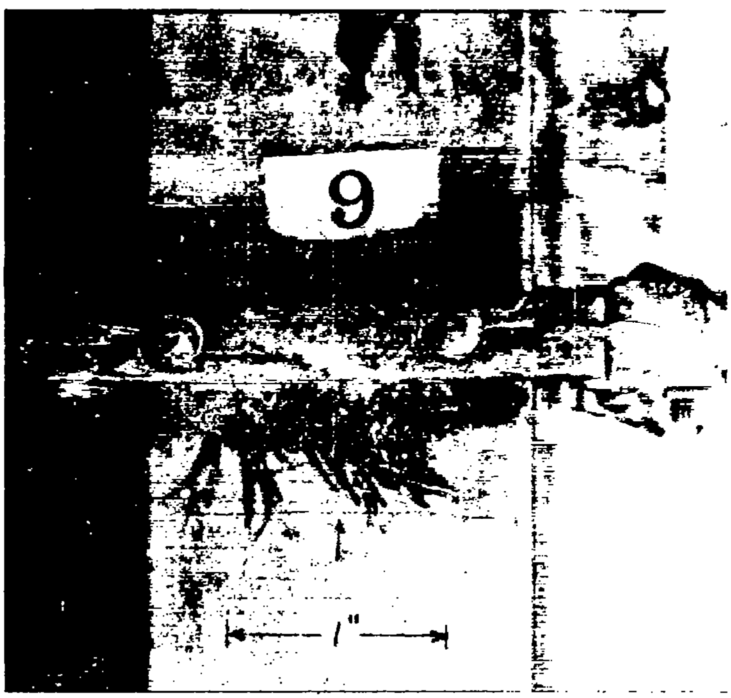


Figure 16.- Two views of the fracture of specimen 9.

Figure 17.- Two views of the fracture of specimen 10.